The Aquitaine Basin: oil and gas production in the foreland of the Pyrenean fold-and-thrust belt New exploration perspectives

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ABSTRACT

The Aquitaine Basin of southwestern France lies in the foreland of the Pyrenean fold-and-thrust belt. Since the first gas discovery in 1939, the area has produced as of December 1993 a total of $287 \cdot 109\ m^3$ of gas (±10 TCF), $10.2 \cdot 10^6$ t of condensates ($75 \cdot 10^6$ bbl) and $12.3 \cdot 10^6$ t of oil ($\pm 90 \cdot 10^6$ bbl).

The structural evolution of this basin was strongly influenced by early basement tectonics dating from the Variscan and Hercynian orogenies. The subsequent evolution was governed by extensional block faulting and associated salt diapirism during Jurassic and Early Cretaceous times, and by compressional deformations during the Late Cretaceous through the Oligo-Miocene Pyrenean Orogeny. Thus the Aquitaine Basin underwent a complex evolution, both structurally and stratigraphically.

Kimmeridgian and Barremian shales are the most prolific source-rocks. These have variably entered the oil and ultimately the gas generation windows during Early Cretaceous to Paleogene times. Hydrocarbon accumulations are trapped in tilted fault blocks involving Jurassic and Barremian carbonates, which developed during an Early Cretaceous phase of crustal extension, as well as in Jurassic and Barremian erosional reservoir pinch-outs over salt-induced structures which developed at the same time; these features were inverted to various degrees during the Pyrenean orogeny.

In this particularly complex structural setting, conventional 2D seismic provided generally poor resolution. From 1987 to 1993, over 1300 km^2 of 3D seismic were acquired with the dual purposes of field development and oil and gas exploration. These good quality subsurface data have allowed us to define the distribution, geometries and relationship between the different tectono-stratigraphic units as well as to image structures providing potential hydrocarbon traps. As a result, our understanding of the geodynamic evolution of the entire basin, as well as of the dynamics of its petroleum systems, was greatly enhanced. This new understanding has opened new perspectives for oil and gas exploration in the entire Aquitaine Basin.

Le Vot, M., Biteau, J. J. & Masset, J. M., 1996. — The Aquitaine Basin: oil and gas production in the foreland of the Pyrenean fold-and-thrust belt. New exploration perspectives. *In*: Ziegler, P. A. & Horváth, F. (eds), Peri-Tethys Memoir 2: Structure and Prospects of Alpine Basins and Forelands. *Mém. Mus. natn. Hist. nat.*, **170**: 159-171 + Enclosures 1-6. Paris ISBN: 2-85653-507-0.

This article includes 6 enclosures.

Source : MNHN, Paris

INTRODUCTION

The Aquitaine Basin of Southwestern France forms the northern foreland of the Pyrenean Mountain Belt (Encls. 1a and 1b). During the last 60 years, exploration in the area has led to the discovery of ultimate recoverable reserves amounting to over $350 \cdot 109$ m^3 of gas (12.5 TCF) and $90 \cdot 10^6$ t of oil ($660 \cdot 10^6$ bbl). Thus, the South Aquitaine area represents the largest gas producing and the second larges oil producing province of France.

Exploration in the Aquitaine Basin started in the 1930's and resulted in 1939 in the discovery of the St. Marcet gas field which has recoverable reserved of $8 \cdot 10^9$ m^3 of gas (290 BCF). The discovery well was drilled on a surface anticline. The potential of the area was later on confirmed by the discoveries of the Upper Lacq oil field in 1949, the giant Deep Lacq gas/condensate field in 1951 ($260 \cdot 10^9$ m^3 gas, 9.2 TCF) and the Meillon gas field in 1965 ($65 \cdot 10^9$ m^3 gas, 2.3 TCF). In the same area, several smaller sized fields, such as Ucha, Lacommande, Rousse and Cassourat fields, each having gas reserves in the 3 to $7 \cdot 10^9$ m^3 range (110-250 BCF), were also discovered in the same period. In the 1970's, exploration interests moved northward towards the basin edge, resulting again in the discoveries of five sizeable oil fields, namely Pecorade, Vic Bilh, Lagrave, Castera Lou and Bonrepos-Montastruc (Encl. 1b).

By now two hydrocarbon fairways are recognized. The southern gas trend is associated with the leading edge and the proximal parts of the foreland of the Pyrenean fold-and-thrust belt. The northern oil trend is tied to the distal margin of the foreland basin (Encl. 1b). The distribution of the oil and gas fields also demonstrates the variety of the area's hydrocarbon occurrences (leading edge of the thrust belt and general foreland area).

In the evolution of the Aquitaine Basin Hercynian basement features played a critical role. The Mesozoic and Cenozoic palaeogeographies and tectono-sedimentary units are overprinted on an inherited framework of basement discontinuities (Villien and Matheron, 1989). The complex, post-Hercynian (Triassic and younger) geodynamic evolution of the basin can be summarized as follows (Encl. 1c):

(1) During the Jurassic and Early Cretaceous, regional extension was related to the opening of the Atlantic Ocean (Canérot and Delavaux, 1986; Canérot, 1987; Canérot, 1989; Villien and Matheron, 1989). Throughout this entire period generally WNW-ESE extensional stresses played a controlling role. The paroxysm of extension took place during the Aptian-Albian, resulting in sinistral transcurrent motions between the Iberian and European plates. Rapid subsidence of Early Cretaceous pull-apart basins in the area of the Aquitaine Basin involved transtensional reactivation of major Hercynian fault zones.

(2) During Late Cretaceous to Oligo-Miocene times, regional North-South compression was related to the subduction of the Iberian Plate beneath the European Plate (Roure and Choukroune, 1992). This was accompanied by the uplift of the intracratonic Pyrenean fold-and-thrust belt (Encl. 1a). The Pyrenees are characterized by an upthrusted internal crystalline core which is flanked by the opposite verging northern and southern external fold-and-thrust belts. The Pyrenean diastrophism resulted in a fundamental reversal of the earlier palaeogeographic setting of the Aquitaine Basin.

This paper summarizes the geological domains, the structural styles as well as the geological evolution of the Aquitaine region. It is based on an integration of numerous wells and the available 2D and 3D reflection-seismic data. In the concluding chapter, the main parameters controlling the petroleum systems of the Aquitaine Basin are described.

REGIONAL GEOLOGY

From North to South the area can be subdivided into three distinct geological provinces, namely

Source : MNHN, Paris

the North Aquitaine Platform, the Pyrenean Foreland and the Pyrenean Mountain chain (Encls. 1a and 1b, 2a).

North Aquitaine Platform

The North Aquitaine Platform occupies the northern, distal parts of the Aquitaine Basin (Encl. 2). This stable platform shows a moderately complete Mesozoic and Cenozoic stratigraphic sequence which rests unconformably on the Palaeozoic basement (Encl. 1c). Overlying basal Triassic and Liassic evaporites, the sedimentary section is thin and consists mainly of carbonates. Although good closures associated with large amplitude salt domes do exist, the hydrocarbon potential of this zone is poor due to insufficient maturation of the source-rocks, as well as a lack of efficient seals.

Pyrenean Foreland Basin

This province contains all major discoveries in the Aquitaine Basin. Structuration of the foreland was primarily acquired during the Early Cretaceous extensional phase which controlled the subsidence of the Arzacq and Tarbes basins (Encl. 2). These basins, which contain over 5000 m of Barremian to Albian sediments, are flanked by Early Cretaceous platforms and salt ridges. The latter are located along the margins of these basins. The Arzacq and Tarbes basins were partially inverted during the Late Cretaceous and Tertiary phases of the Pyrenean orogeny.

Pyrenean Fold-and-Thrust Belt

The East-West striking Pyrenees extend over a distance of some 400 km from the Mediterranean Sea to the Atlantic Ocean (Encl. 1a). Their internal core, formed by upthrusted and out-cropping basement blocks, is flanked to the South and the North by thin skinned fold-and-thrust belts, involving Mesozoic sediments which are detached from the basement at the level of Triassic-Early Jurassic evaporites. On the southern, Spanish side, compressional deformations are mainly Tertiary in age; shortening related to southward thrusting is of the order of 50 to 70 km. On the northern, French side, most of the shortening is concentrated in the internal zone and is primarily Late Cretaceous in age, as documented by the development of a syntectonic Cenomanian to Maastrichtian foredeep basin (Encl. 2). Shortening associated with Tertiary northward thrusting is minor and is thought to be of the order of 20 km.

GEODYNAMIC EVOLUTION

Palaeozoic

The structural framework of the Palaeozoic basement, which was acquired during the Late Carboniferous Hercynian orogeny, was studied along the margins of the Aquitaine area by Winnock (1971), Autran and Cogné (1980), Cogné and Wright (1980), Paris (1984) and others. Two major sets of basement faults characterize these early deformations; these faults strike N110° and N160° and are associated with conjugate systems oriented at N20° and N50°-70°, respectively (Encl. 1b). These fault trends represent important basement discontinuities which were reactivated during the Permo-Carboniferous Late Hercynian tectonic phases. The Mesozoic and Cenozoic palaeogeographies and the respective tectono-stratigraphic units appear to be largely controlled by these main basement fault systems.

Source : MNHN, Paris

Triassic To Early Liassic

During Triassic to Early Liassic times, the entire Aquitaine Basin was characterized by a high rate of tensional subsidence, accounting for the deposition of a thick, uniform sequence of anhydrites and salts across the entire area (Encl. 1c; Curnelle, 1983). The presence of this evaporitic cushion is a key element for the future geodynamic evolution of the Aquitaine Basin, as this ductile body was easily remobilized during subsequent tectonic movements and/or differential rates of sedimentation (Canerot and Lenoble, 1993).

Middle And Late Jurassic

This period was characterized by the early opening phases of the Atlantic Ocean. The Middle and Late Jurassic evolution of the Aquitaine Basin was controlled by a low rate of extension which was guided by WNW-ESE directed extensional stress systems. As a result, the Jurassic subsidence patterns were primarily controlled by the reactivation of inherited faults which strike close to perpendicular to the main stress direction (essentially the N20° and N50°-70° sets of faults). During the Middle and Late Jurassic, the basin was characterized by a calm carbonate platform which generally deepened westward (Encl. 1c).

The Oxfordian to early Kimmeridgian period corresponded to a phase of differentiation of this platform in response to active crustal extension (Encl. 3a; Canérot, 1987). The basin was subdivided into an inner shelf with evaporitic tendencies to the East (dolomites and limestones of the Meillon and Baysere Formations; Encl. 1c) and a more open marine environment to the West (Oxfordian Ammonite Marls and lower Kimmeridgian shaly limestones of the Lower Cagnotte Formation). Following this phase of differentiation, middle to late Kimmeridgian times corresponded to a period characterized by a stable depositional environment; locally condensation was related to synsedimentary salt tectonics along North-West and North-East trending basement faults. These local events, which are related to the reactivation of earlier extensional faults, were of minor importance.

At the end of the Jurassic, the Late-Cimmerian tectonic phase was accompanied by a general regression. The dolomitic facies of the Mano Dolomite (average thickness 200 m; Encl. 1c) is associated with this regressive cycle. During the late Portlandian, the basin became again separated into two domains along a northerly trend which was already evident during the Oxfordian to early Kimmeridgian tensional phase (Encls. 3a and 3b). The eastern shelf was uplifted and subjected to erosion, as evident by the regional deposition of the Portlandian dissolution breccias of the Garlin Formation (Encl. 3b) and the development of a hiatus spanning end-Portlandian to Barremian times. In the western part of the basin, sedimentation continued under gradually increasing water depth; here a dolomitic environment of deposition, controlled by North-South directions, persisted during Portlandian, Berriasian and Hauterivian times.

Early Cretaceous

The Early Cretaceous geological evolution of the Aquitaine Basin was marked by the paroxysm of general East-West extension which governed the gradual and step-wise opening of the North Atlantic Ocean, the mid-Aptian onset of opening of the Bay of Biscay and the ensueing sinistral motion of Iberia relative to Europe.

In the Aquitaine Basin, a high rate of transtensional deformation is evidenced by important strike-slip motions along the N110° and N160° inherited basement faults. Although the major transcurrent motions took place along the European-Iberian plates boundary, the entire region was affected by important strike slip movements. The Jurassic platform was delaminated along these main fault zones (Canérot, 1989), allowing for the development of the deep, confined, lozange-shaped Arzacq and Tarbes basins which are characterized by NW-SE trending depocentres (Encls. 3b and 3c; Bourrouilh et al., 1995). The sedimentary record of these basins permits to establish three major periods of subsidence associated with this extensional phases:

Source : MNHN, Paris

Barremian to early Aptian

The Early Cretaceous palaeogeography was initiated during this period. Depocentres were characterized by very thick deposits, while the surrounding platforms showed a very low rate of subsidence and sedimentation. Rapid subsidence of the Arzacq and Tarbes basins was accompanied by the main phase of diapiric salt movements along their edges. This involved the migration of Triassic and Liassic evaporites away from the subsiding depocentres towards their margins (Encl. 3b).

Latest Aptian to early mid (?) Albian

A platform-basin configuration was acquired during this period. The Arzacq and Tarbes basins were again characterized by very high subsidence and sedimentation rates. The platform-basin transition zones were marked by the development of a system of patch reefs (Encl. 1b) whereas the platforms proper were characterized by low sedimentation rates.

Late Albian

During the late Albian the palaeogeography of the Aquitaine Basin changed completely and was controlled by important tectonic movements taking place along the Iberian-European plates boundary (Peybernes and Souquet, 1984). As a result, subsiding zones shifted to the South towards this very mobile zone, while a major transgression invaded the entire area. Late Albian sediments overlap the earlier basin margins, thus demonstrating a change in controlling stress systems at this time. In fact, this period corresponded to the transition from the general East-West extension, which had prevailed during the Jurassic and Early Cretaceous, to the northerly directed Pyrenean compression which controlled the evolution of the basin during the Late Cretaceous and most of the Tertiary.

The Early Cretaceous palaeogeographic framework of the area is particularly well preserved in the foreland area where Pyrenean inversion movements were of minor importance. The Arzacq Basin in particular (Encls. 1b and 3c) allows to describe the various tectono-sedimentary units which developed during the Early Cretaceous extension. From the edges to the centre of this basin three main elements can be distinguished:

Salt ridges surround the basin on all sides (Encls. 1b and 2). They developed by migration of the Triassic and Liassic evaporites from the subsiding depocentres towards the basin margins (Encl. 3c). Salt ridges are well expressed on the northern side of the Arzacq Basin (Audignon, Garlin, Antin and Maubourguet salt structures, see Encl. 1b) where their original geometries have been only slightly modified during the Pyrenean compression phases (Encls. 2b to 2d). Along the southern basin margin, at the level of the Grand Rieu palaeohigh (Encls. 1b and 2), the salt has either been completely eroded along the axis of the Late Cretaceous foredeep or has migrated away during the Pyrenean compression. The main phase of salt tectonics took place during the earliest Cretaceous period, as shown by Barremian limestones or early Aptian shales, sealing erosional pinch-outs of Jurassic strata along the salt ridges (Encls. 3a and 3c). Latest salt movements, of minor importance, occurred during late Aptian and Albian times; locally this is demonstated by Late Cretaceous sediments resting directly on the salt domes. Along the edges of the Arzacq Basin, traps for the oil and gas fields were clearly formed during this episode of salt tectonics (Encls. 1b, 2d and 3b).

Early Cretaceous Platforms surround the Early Cretaceous depocentres and are located between the basins and the salt ridges (Encls. 1b and 5a). These platforms are characterized by a continuous but slow rate of sedimentation throughout Barremian to late Albian times. The platform-basin transition was marked by the development of Albo-Aptian patch reefs, which have been recognized in several wells (e.g. Lacq, Morlaas, Boucoue and Theze reefs; Encl. 3c). These reef build-ups permit to date the main extensional phase as late Aptian to mid Albian. The lack of oil exploration successes at the level of these reefs can be explained primarily by the lack of efficient topseals, but also by the remoteness of these features

Source : MNHN, Paris

from the main hydrocarbon generating kitchens (Encl. 1c). On the other hand, Jurassic objectives on the platforms are ideally located, namely in structural continuity and updip from basinal areas in which Barremian and Kimmeridgian shaly limestones, representing the principal source-rocks, have reached maturity for oil and gas generation (Encls. 2c and 2d).

The **Early Cretaceous Arzacq and Tarbes basins** correspond to zones of maximum subsidence. Good quality 2D seismic data permit to evaluate the evolution of the Arzacq Basin (Encl. 5a). Differential extensional subsidence of this basin commenced during the Barremian and early Aptian, as indicated by important thickening of the respective sediments from the adjacent platforms into the basin. Halokinetic movements, occurring during this period, can be directly related to the high subsidence and sedimentation rates characterizing this basin. Latest Aptian through middle Albian times correspond to the main episode basin subsidence, as again evidenced by thickening of the respective sediments into the basin. The lack of contemporaneous major salt tectonics suggests, that most of the salt had already migrated away from the basin centre during the Barremian and early Aptian episode of extensional basin subsidence.

Late Cretaceous

The Pyrenean compressional deformation of the Aquitaine Basin clearly commenced at the beginning of the Late Cretaceous. During this time, deformations were mainly concentrated on the internal zone of the Pyrenees where they correspond to the main phase of basement thrusting and faulting. Deformation of the associated forelands involved the development of important uplifts along East-West trending palaeostructures, such as the Grand Rieu palaeohigh and Meillon gas field monocline (Encl. 1b), as well as important strike-slip movements along transverse striking (N20°, N50°-70° and N160°) inherited fault zones.

In this general structural environment the Late Cretaceous palaeogeography was dominated by two major depositional domains (Encl. 3d).

During Cenomanian to Maastrichtian times, the southern parts of the area were occupied by a **thrust-loaded foredeep basin**, located immediately to the North of the internal core of the Pyrenean mountain chain (Encls. 2c and 2d, 3b). This basin corresponds to an E-W trending asymmetric, narrow flysch trough (Dubois and Seguin, 1978). Near the Late Cretaceous deformation front, clastics derived from the rising Pyrenees, attain thicknesses of over 3000 m and thin out northwards (Encl. 2). This palaeogeographic setting was initiated during the Cenomanian; the axis of this foredeep basin migrated northward from Cenomanian to Maastrichtian times (Encl. 3d). Erosional pinch-outs of the Cenomanian to Santonian deposits are associated with pre-Campanian uplifts along the Meillon gas field monocline. As a result of these uplifts, Early Cretaceous sediments were deeply truncated by this unconformity (Encl. 2d). The distribution of the Campanian Soumoulou breccias, which consists of reworked Cretaceous sediments, is limited to the flanks of such uplifted structures (Encl. 3d).

The flysch dominated foredeep was offset to the North by a wide **stable carbonate platform** which persisted during Cenomanian to Maastrichtian times (Encl. 3d; Dubois and Seguin, 1978). It is important to point out that, along the southern limit of this platform, Cenomanian carbonates rest unconformably on late Albian sediments; this unconformity fades out northwards. Cenomanian to Maastrichtian platform carbonates attain thicknesses in the 250 to 1250 m range. The Upper Lacq and the Lagrave oil fields produce from Late Cretaceous platform carbonates (Encls. 1b and 1c).

Tertiary

After a period of tectonic stability at the Cretaceous-Tertiary transition, during which the on average 100 m thick Danian limestones were deposited over the entire foreland, North-South compressional deformation of the basin resumed. The main tectonic pulses occurred primarily during Ypresian, Eocene and Oligo-Miocene times. These compressional phases were responsible for the structuration of the Pyrenean fold-and-thrust belt as well as for limited inversion of the northern salt

Source : MNHN, Paris

ridges (Encls. 2b to 2d). The N 20°, N 50°-70° and N 160o striking transverse fault zones, located in the most external part of the foreland, showed again evidence for important strike-slip movements (e.g. Seron fault zone, Encl. 1b).

Following Late Cretaceous basement faulting, Tertiary compression was characterized by thin skinned tectonics in the external parts of the Pyrenean fold-and-thrust belt. The structural geometry of resulting structures appear to be controlled by the earlier palaeogeographies.

For instance, to the West, in the area of the Sainte-Suzanne salient (Encl. 1b), a thick Early and Late Cretaceous sedimentary section overlays thick Triassic and Liassic evaporites (Encl. 2b). Maximum shortening associated with Tertiary thrusting occurred in this zone and involved the activation of a single decollement level, corresponding to the Triassic and Liassic evaporites. In conjunction with these deformations, the Cretaceous basins and salt domes were inverted (Encls. 2a and 2b). Immediately to the East of the Sainte-Suzanne salient, (Encls. 1b, 2a and 2c), the frontal thrust ramps up laterally along the western margin of the Arzacq Basin in the area of the deep Lacq gas field. Still on the same trend, further to the East, in the area of the Grand Rieu palaeohigh (Encl. 1b), most of the thrust deformations were confined to the South of this basement high which corresponds to the southern palaeo-margin of the Arzacq Basin (Encls. 2a and 2d).

As such, these observations highlight the importance of the different structural inheritances (Hercynian, Jurassic, Early Cretaceous) on the structural style of the area. Basement highs, which delimit the Early Cretaceous basins, acted as buttress zones during the Pyrenean compression (Encl. 1b). As a result of this structural configuration, basal thrusts ramp up section from the Triassic and Liassic evaporites to the basal Late Cretaceous unconformity (Encls. 2b to 2d). To the North, most of the Tertiary deformation thus affected only the Late Cretaceous and Tertiary part of the sedimentary sequence, while Jurassic and Early Cretaceous sediments were not deformed. (e.g. Meillon gas field, see Encls. 2c and 2d).

During Late Cretaceous to Oligocene times, Pyrenean compressional deformations propagated northwards, as documented by a piggy-back sequence of deformation. This evolution is evident within the thrust belt itself, where it images a northward migration of the deformation front from the internal zone to its present leading edge. In the foreland, the different periods of active shortening reflect a similar northward progression of deformation and foredeep migration.

PETROLEUM GEOLOGY

Most of the oil and gas fields which were discovered in the Aquitaine Basin are associated either with Late Cretaceous carbonate platforms (e.g. Upper Lacq and Lagrave oil fields), with Jurassic/Early Cretaceous inherited structures located along the northern, western and southern margins of the Arzacq Basin or with partly inverted Early Cretaceous salt ridges along the northern margin of the Arzacq Basin (Vic Bilh, Pecorade, Castera Lou oil fields) as well as its southern margin (Ucha, Lacommande, Rousse and Cassourat gas fields). The largest fields are the Deep Lacq and the Meillon gas fields; these are located in the transition zone between the Early Cretaceous Platform and the southward adjacent deeper-water basin (Encls. 1b, 1c, 2a, 2c and 2d).

Reservoirs (Encl. 1c)

Jurassic dolomites and Barremian limestones represent the main hydrocarbon reservoirs. Their distribution is closely linked to the Jurassic and earliest Cretaceous palaeogeographies. In accordance with the palaeogeographic provinces described above, two domains can be distinguished (Encls. 3a and 3b).

On the **eastern Jurassic shelf**, reservoirs are represented by the early Kimmeridgian Meillon dolomites (average thickness 200 m), the Portlandian Mano dolomites (150-200 m) and the Garlin Breccias (Encls. 1c and 3b). In the Meillon, Ucha, Lacommande and Rousse trend of structures, these reservoirs are totally or partially gas

Source : MNHN, Paris

bearing. Although porosities of Jurassic carbonates are rather poor (2 to 4% matrix porosity for the Mano dolomites and 4 to 8% for the Meillon dolomite), effective permeability is primarily provided by fissures and fractures, allowing for good well productivities.

On the **western Jurassic outer shelf** (Lacq, Pecorade and Vic Bilh fields; Encls. 1b, 3a and 3b), only the Mano dolomites are preserved within the Jurassic sequence (Encl. 3b). Although petrophysical characteristics are better here, they remain in average poor (porosity 2-10%). Production is again primarily associated with intensely fractured reservoirs.

In this same area, upper **Barremian limestones** provide a further reservoir, displaying porosities varying between 10 and 15%. Permeabilities are relatively poor but often enhanced by the intense fracturing.

On the **Late Cretaceous platform**, reservoirs are formed by the 200 to 250 m thick Lower Senonian limestones (Encls. 1c and 3d). The good reservoir characteristics of these limestones (10 to 25% matrix porosity) are closely linked to secondary dolomitization in the vicinity of the main Pyrenean faults. The example of the Lagrave oil field demonstrates that dolomitization decreases some distance away from the Tertiary Seron transcurrent fault system, resulting in lateral reservoir deterioration (Encl. 2a).

Source-Rocks (Encl. 1c)

Important reserves of oil and large amounts of gas have been discovered in the Aquitaine Basin, implying that source-rocks of regional extent are available, have a good hydrocarbon generation potential and have expelled significant quantities of oil and gas. Although some source potential has been recognized in Tertiary, Albian and Liassic shales, these formations have contributed little and the main source-rocks are clearly associated with the Barremian and Kimmeridgian formations. This is confirmed by the geochemical source-rock to oil and source-rock to gas correlations, summarized in Enclosures 4a and 4b.

The marine **Barremian source-rocks** contain type II-III organic matter. Across the basin they enter the oil window on average at depths of -3000 m, while the gas window is reached at –4000 m (Encls. 4c and 4d). Hydrocarbon generation and expulsion started during the late Albian in the Early Cretaceous depocentre of the Arzacq Basin and expanded during the Tertiary to both sides of the basin (Encl. 4c).

The marine **Kimmeridgian source-rocks** appear to have the best petroleum potential. Their organic matter is again primarily of type II-III. TOC values range between 2 and 7% (Espitalié and Drouet, 1992) with values of S2 up to 20 kg/t rock.

Trapping Mechanisms

The traps of the different fields are clearly related to structures inherited from the Early Cretaceous extension (platform-basin transition, see Encls. 1b and 4d) and associated salt tectonics along the margins of the Arzacq and Tarbes basins (erosional pinch-outs of the Jurassic and Barremian reservoirs, Encls. 2a, 2c and 3b). These traps were modified during the Pyrenean orogeny which is responsible for the present structural configuration of the area (Villien and Matheron, 1989). Under such a structural setting, fields are primarily located in the proximal (Lacq, Meillon, Ucha, Lacommande, Rousse fields; Encls. 1b, 2d and 3b) and distal foreland (Vic Bilh, Castera Lou, Lagrave fields; Encls. 1b and 4d) and also within the Pyrenean fold-and-thrust belt (Saucede and Ledeuix fields; Encls. 2b and 4d). In the following, selected examples of accumulations are described and their structural evolution discussed.

Rousse and Lacommande gas fields

These fields are located in the proximal parts of the Pyrenean foreland and are contained in structures which developed in conjunction with Early Cretaceous salt tectonics. Acquisition of the

Source : MNHN, Paris

3D Meillon surveys in 1989-1990 has greatly advanced our understanding of the geometry of the Rousse and Lacommande fields and the geodynamic evolution of these traps which produce from erosionally truncated Jurassic carbonates, sealed by Barremian carbonates, early Aptian shales and Late Cretaceous flysch (Encls. 6a to 6c).

Development of these structures was initiated by Barremian to early Aptian diapirism of the Triassic-Liassic salts along the Grand Rieu palaeohigh, forming the southern margin of the Arzacq Basin, resulting in uplift and erosion of the Jurassic reservoir section over the crest of the evolving diapirs (Encls. 3b, 3c, 4d and 6b). The truncated Jurassic reservoirs were sealed by Barremian carbonates and early Aptian and Albian shales (Encls. 3b and 3c). These Early Cretaceous structures were inverted during the Late Cretaceous compressional phase while the Albian sediments above the Rousse and Lacommande structures, as well as over the salt ridges, were eroded in the area of the Grand Rieu palaeohigh along the syntectonic Late Cretaceous foredeep. During the Tertiary compressional phases, the basal Late Cretaceous unconformity acted as a decollement level along which Late Cretaceous and younger series were thrusted northwards (Encls. 2d and 6c).

The structures containing the Lacommande and Rousse gas fields developed therefore very early on during the geological evolution of the area, but were subsequently repeatedly modified. As Jurassic source-rocks were truncated to the North and South of these structures, a local hydrocarbon charge must be implied. Generation and expulsion of hydrocarbons from these source-rocks commenced during the Eocene and persisted during the Oligo-Miocene period and, thus, clearly post-dated the structuration of these traps (Encl. 4d).

These traps rely on a combination of seals. Their southern flanks are sealed by Late Cretaceous flysch whereas their northern, eastern and western sides are sealed by preserved Early Cretaceous sediments which include over-pressured shaly limestones. Top seals are provided by Barremian carbonates and Late Cretaceous flysch (Encl. 6c).

Meillon gas field

Early Cretaceous salt and extensional tectonics and Late Cretaceous uplift and strike slip movements played an important role in the development of the Meillon structure, the geometry of which is also defined by 3D seismic data (Encls. 6a to 6c). This field is located along the platform-basin transition zone on the southern side of the Arzacq Basin (Encl. 3c). The trap corresponds to a 30 km long monocline which dips at 20° to 30° to the North and is upheld by Jurassic and Barremian carbonates (Haller and Hamon, 1993). This structure is bounded on its southern side by an Early Cretaceous normal fault. The monocline is cut by inherited transverse N20° and N160° striking faults.

Initial development of this structure is related to Barremian to early Aptian salt tectonics along its southern limit. Well data show that truncated Jurassic reservoirs are sealed by Barremian and early Aptian sediments on the northern flank of the Meillon monocline. The normal fault, delimiting the field to the South, is related to latest Aptian-middle Albian extension. Late Cretaceous uplift and strike slip motions in the proximal foreland, associated with the early Pyrenean compression phase, are responsible for the present configuration for the field. Tertiary compression affected, however, only the Late Cretaceous and Tertiary sediments which are thrusted northwards over the deep seated Meillon block.

As a result of its configuration, this trap relies on a combination of seals, namely Barremian tight shales and carbonates on the monocline and latest Aptian through middle Albian over-pressured shaly limestones along its southern, faulted flank.

The Meillon field relies for charge on hydrocarbons generated in the Arzacq Basin depocentre. The evolution of the area, as well as organic geochemical studies, suggest two phases of generation and migration of hydrocarbons from the Arzacq Basin into the Meillon structure. During the Early and Late Cretaceous, the structure was charged with oil. Towards the end of the Cretaceous and during the Paleocene-Eocene the Arzacq kitchen entered the gas window; correspondingly, the oils accumulated in the Meillon structure were partly displaced by gas and partly cracked in situ (Encl. 4c).

Source : MNHN, Paris

Giant Deep Lacq gas field and Upper Lacq oil field

Early Cretaceous salt and extensional tectonics and Late Cretaceous and Tertiary compressional deformations contributed to the development of the anticlinal Lacq structure. The recently acquired 3D seismic survey over the Lacq field had a huge impact on the general understanding of the geometry of this structure, its geological evolution which led to the formation of the trap and the dynamics of its petroleum systems (Encls. 1b and 6d).

The Deep Lacq gas field produced from Late Jurassic and Barremian carbonates along the platform-basin transition on the southwestern side of the Early Cretaceous Arzacq Basin. It is located in a particular structural setting, characterized by three main faults trends, striking N20°, N110° and N160° (see Encls. 1b and 3c). The present, trap providing structure is the result of multi-phase deformations.

During the Oxfordian to Portlandian extensional phase, the Lacq field area was located along the eastern limit of the Jurassic open marine outer shelf (Encls. 3a and 3b). During Barremian times, the area remained stable and eustatic sea-level fluctuations mainly controlled the sedimentary evolution of the gas reservoirs.

Due to its particular setting, the Early Cretaceous evolution of the Lacq structure differs from that of other structures. Salt tectonics were initiated during the early Aptian and culminated during the latest Aptian to Middle Albian and thus coincided with the major extensional subsidence phase of the Arzacq Basin. Early growth of the Lacq salt structure is held responsible for the localization of the Aptian-Albian Lacq reef.

Following minor compressional deformations during the Late Cretaceous, the Lacq field acquired its present structural configuration during a phase of Tertiary compression. Most of the movements were located within the Triassic-Liassic evaporites, causing accentuation the asymmetric geometry of the structure by southward migration of the evaporites. The resulting uplift led to the formation of the Upper Lacq structure. 3D seismic data show that the salt swell, upholding the Jurassic anticlinal feature of the Deep Lacq gas field, has a thickness of about 2000 m. Movements along the Ste. Suzanne thrust fault, which ramps up section along the northwestern side of the Lacq structure, took place at the same time (Encl. 6d).

The Deep Lacq gas/condensate accumulation is trapped in the uppermost Jurassic Mano dolomites, Purbeckian to basal Barremian carbonates (lower Annelides, 310-510 m thick) and upper Barremian limestones (upper Annelides, 40-75 m thick). The intra-Barremian laterolog shales (±50 m) separate the two reservoirs. The deeper Jurassic to basal Barremian reservoirs contain the giant gas/condensate accumulation whereas the upper Annelides limestones contain no-commercial gas and oil lenses.

Recent studies by Connan and Lacrampe-Couloume (1993) show that the Jurassic and lower Barremian reservoirs were charged by hydrocarbons generated from the Kimmeridgian Lons Formation whereas the upper reservoir received its charge from the uppermost Barremian "Calcaires à Annelides" which are located within the oil window in the Lacq structure (autochthonous origin). In contrast, the gas and condensate accumulation contained in the Jurassic carbonates was most likely generated by very mature source-rocks; this is compatible with the maturity of Kimmeridgian source rocks in drainage areas offsetting the Lacq structure (Encl. 4d). Moreover, geochemical characteristics of the fluids reflect intense cracking and interaction of both gas and condensates with anhydrites (H_2S content) in the reservoir (Connan and Lacrampe-Couloume, 1993).

The top seal of the deep Lacq gas field is provided by the "laterolog shales" and by upper Barremian anhydrites whereas over-pressured Albo-Aptian shaly limestones form the lateral seal of this accumulation (Encl. 6d).

The reservoir of the Upper Lacq oil field is formed by Late Cretaceous carbonates (Encls. 1c and 6d). Oil to source-rock correlations show that sourcing is from the uppermost Barremian "Calcaires à Annelides". Migration of oil from this deeper level was associated with the fracking of the lower Aptian shales during the Tertiary.

Source : MNHN, Paris

Lagrave oil field

The Lagrave field is located along the eastern margin of the Early Cretaceous Arzacq Basin on the Late Cretaceous platform in the Pyrenean foreland (Encl. 1b). The Lagrave field is structurally trapped and produces from early Senonian limestones of the Jouansalles Formation. The good petrophysical characteristics of this reservoir are due to secondary dolomitization of the Jouansalles limestones along the Seron Fault zone. The trap of this field developed in response to sinistral strike slip movements along the inherited Early Cretaceous Seron Fault zone during the Tertiary phases of the Pyrenean Orogeny. The top seal for the field is formed by late Senonian shales of the Pé-Marie Formation whereas lateral seals are provided by the syntectonic Ypresian flysch (Encl. 4d).

Oil to source-rock correlations show that hydrocarbon charge was again provided by Barremian and Kimmeridgian shaly limestones.

An analysis of the area shows that the original closure at the level of the Senonian reservoir of the Lagrave structure was formed by compaction-drape over a deep seated fault block, involving the Jurassic carbonates. Hydrocarbon charge to this early structure occurred during the Paleocene. During the Oligo-Miocene this structure was compressionally modified; at the same time fracturing of the Early Cretaceous seals permitted migration of light oil from the Jurassic source-rocks and reservoirs into the Late Cretaceous reservoirs.

VIc Bilh oil field

This field is located in the distal parts of the Pyrenean foreland, along the northeastern margin of the Arzacq Basin, which was affected by Early Cretaceous salt tectonics and limited inversion during the Tertiary Pyrenean phases. The trap of this field is formed by an erosional pinch-out of Jurassic carbonates along the northern salt ridges of the Arzacq Basin (Encls. 1b and 4d). The main halokinetic episode is again pre-Barremian in age, as attested by the transgression of the Barremian and early Aptian sediments over deeply eroded Jurassic carbonates and Triassic and Liassic evaporites at the top of the salt dome (Encl. 4d). The reservoir comprises the Portlandian Mano dolomites and Barremian limestones. The top seal is formed by the early Aptian shales of the Sainte-Suzanne Formation; Albo-Aptian shaly limestones are thought to provide lateral seals.

The oil contained in the Vic Bilh structure was derived from Kimmeridgian and Barremian source-rocks which probably reached maturity during the Oligo-Miocene at the same time as the trap was closed.

CONCLUSIONS

The geology of the northern Pyrenean fold-and-thrust belt is very complex; its structural style is primarily controlled by inherited trends which were repeatedly reactivated during younger tectonic pulses. Structures which developed during the Jurassic and Early Cretaceous extensional phases are generally faulted blocks which were modified to various degrees by salt tectonics. The reconstruction of early formed, Early Cretaceous structures and an understanding of their regional palaeogeographic setting are considered to be essential steps before proceeding further. During the Late Cretaceous to Oligocene Pyrenean Orogeny, pre-existing structures were reactivated to various degrees and at different periods. These polyphase deformations are responsible for the great variety of prospective structures in the Aquitaine Basin.

A similar diversity characterizes the petroleum systems of the Aquitaine Basin. The most prolific source-rock is the Kimmeridgian Lons Formation; however, a significant contribution to hydrocarbons generated and accumulated comes also from Barremian shales. The timing of generation, expulsion and migration phases ranges from Early Cretaceous to Late Tertiary with a progressive evolution closely linked to the local tectonic evolution of each area. To date roughly $330 \cdot 10^6$ tons ($2.4 \cdot 10^9$ bbl) of oil and oil equivalent have been proved up in around fifteen fields.

Source : MNHN, Paris

In such a context the challenge for the petroleum explorationist lies in the evaluation of the remaining potential of very complex and unexplored zones to the South of the northern Pyrenean front. Modern 3D seismic data, combined with detailed surface and subsurface geological studies, proved to be essential for the development of a more comprehensive understanding of this complex area and the definition of prospects. Moreover, a validation of geological models and petroleum systems in the foreland is a key to exploration targeting thrusted zones.

The explored parts of the Pyrenean fold-and-thrust belt and its foreland have been proven to be very prolific. The comprehensive studies, summarized in this paper, show that all key parameters necessary for hydrocarbon entrapment and preservation are present also in the unexplored domains of the thrust belt. This gives reasons for an optimistic outlook for future exploration potentials.

Acknowledgments- The authors thank *Elf Aquitaine Production* for releasing this paper for publication and for taking over the cost of colour reproduction of the enclosures. Thanks are extended to Dr. P.E.R. Lovelock and Dr. P.A. Ziegler for their constructive comments on an earlier version of this manuscript.

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Source : MNHN, Paris

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Enclosures

Encl. 1
- a General structural map and regional cross-section through the Pyrenean Mountain chain
- b Aquitaine Basin, general structural map
- c Aquitaine Basin, stratigraphic chart and Petroleum Systems

Encl. 2
- a South Aquitaine Basin, structural framework and Petroleum Provinces
- b Regional cross-section 1
- c Regional cross-section 2
- d regional cross-section 3

Encl. 3
- a General palaeogeographic map of the Aquitaine Basin at the end of the early Kimmeridgian
- b subcrop map at the base of the Cretaceous showing palaeogeography of the Portlandian as was as the erosion due to salt tectonics anolng the edges of the Arzacq Basin
- c Worsm's eye view at the base of the Cretaceous unconformity
- d Map showing the distribution of the upper Cretaceous formations above the base Upper Cretaceous unconformity

Encl. 4
- a Oil to source-rock correlations in the Aquitaine Basin
- b Gas to source-rock correlations in the Aquitaine Basin
- c) General cross-section through the Arzacq Basin showing timing of generation and migration of hydrocarbons in the area as well as the isomaturation levels
- d Aquitaine Basin: traps associated to oil and gas fields in the fold-and-thrust belt and foreland area

Encl. 5
- a 2D seismic line through the Arzacq Basin, time migration
- b 2D seismic section through the Rousse and Meillon fields

Encl. 6
- a South Aquitaine, 3D seismic surveys
- b 3D Meillon survey, Rousse and Meillon gas fields
- c Dip structural cross-section through the Rousse and Meillon gas fields
- d Dip cross-section through the Upper Lacq oil field and the giant Deep Lacq gas field.

Source : MNHN, Paris